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MEASUREMENT OF EMISSIVITY OF INDUSTRIAL SURFACES
USING A SIMPLE METHOD

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16. Abstract To detect the emissivity, the drop in temperature of the sample that is undergoing radiation exchange with the wall in an evacuated space is measured over a given period of time. In this way the emissivities were measured for various synthetic resin lacquers, metals and metallic coatings. If the emissivity is known, the same method can be used to detect the sp. heat and the head condition of gases.					
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Measurement of the emissivity of industrial surfaces using a simple method* **

The measurement of emissivity is very laborious using the usual methods. Thus a new method was developed that, with a simple system and certain test conditions, produces very exact values. In order to measure the emissivity, the temperature decrease is measured over a certain time period in a sample that is located in an evacuated space in radiation exchange with the wall. In this way the emissivity of a number of synthetic resin lacquers, metals and metallic coatings was measured. Using the same method, if the emissivity is known it is possible to determine the specific thermal capacity and the thermal conduction capacity of gases.

The emissivity of a substance is measured by means of its temperature and its radiation properties, which depend on the material and the type of surface. The radiation properties have to be determined experimentally.

Except for special cases, the hemispherical emissivity is used to calculate the thermal transfer by radiation. Taking into account the wavelengths and angle relation of the emission, reflection and absorption leads to complicated radiation exchange calculations and requires extensive measurements of the required radiation properties.

The hemispherical emissivity ϵ is the energy E emitted by a body with an entirely convex surface into a hemisphere, based on the energy E_S that it would emit if it were a black surface¹⁾:

1) Formula symbols at the end of this study.

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*** Numbers in margin indicate foreign pagination.

$$\epsilon = E/E_0$$

(1)

According to the law of Stefan and Boltzmann, if σ is the radiation constant, then

$$E_0 = \sigma T^4$$

(2)

Although there are in the literature extensive numerical data [1] on the hemispherical emissivity of various substances, new measurements are needed all the time, as the description of the surfaces studied is often imprecise and thus the applicability of these data is limited.

The emissivity ϵ is mainly determined by three different measurement principles:

- 1) The spectral distribution of the reflectivity is measured, from which is calculated the emissivity [2].
- 2) The radiation energy emitted by a body is measured directly and compared with that of a black body of the same temperature [3,4].
- 3) The temperature of a sample is measured that is located in an evacuated space in radiation exchange with the surrounding wall, and the electrical energy passed to it is also measured [5].

Only in the case of the last method is the hemispherical emissivity ϵ measured directly. In the case of the other methods the emissivity is measured in the direction of normal or in relation to the angle. For radiation exchange calculations this emissivity, which for most materials does not differ much from the hemispherical emissivity, is sufficiently precise [6].

The measurement method being discussed here is derived from the third method, but it is even simpler, as the sample is not heated. The same measurement principle is used, for example, in space travel, in order to study the radiation exchange of earth satellites in space simulation chambers [7], and to measure the ratio α' that is important for space travel [8] (α = radiation absorption index). In the case of the measurements described in that context, because of the selec-

tion of the sampling arrangement and the test conditions, a high degree of exactness is not achieved.

Measurement method

Let us look at the cooling of a cylindrical rod that hangs centrally in an evacuated tube with a constant wall temperature. The rod has the mass M , the surface F_1 and the absolute temperature T_1 that differs from the temperature of the tube wall, T_2 . The specific heat capacity of the rod material is c . If T_1 is greater than T_2 , the rod cools over a period of time. Since the tube has been evacuated, the heat will be transferred exclusively by radiation between the rod and the tube wall.

The amount of heat given off by the rod to the tube wall during the time dt is

$$dQ = \epsilon_{12} \sigma F_1 (T_1^4 - T_2^4) dt. \quad (3a)$$

ϵ_{12} is the radiation exchange index.

On the other hand, if the temperature within the rod can be considered constant, then the following is true:

$$dQ = -Mc dT_1. \quad (3b)$$

If the rod cools from T_{11} to T_{12} during the time interval t_1 to t_2 , then the radiation exchange index ϵ_{12} can be derived from the differential equation (3): /324

$$\epsilon_{12} = \frac{Mc}{2F_1(t_2 - t_1)\sigma T_2^4} \left[\frac{1}{2} \ln \frac{(T_2 + T_{12})(T_2 - T_{11})}{(T_2 - T_{12})(T_2 + T_{11})} + \arctan \frac{T_2(T_{12} - T_{11})}{T_2^2 + T_{12}T_{11}} \right]. \quad (4)$$

On the other hand, under certain conditions the radiation exchange index is:

$$\epsilon_{12} = \frac{1}{\frac{1}{\epsilon_1} + \frac{F_1}{F_2} \left(\frac{1}{\epsilon_2} - 1 \right)} \quad (5)$$

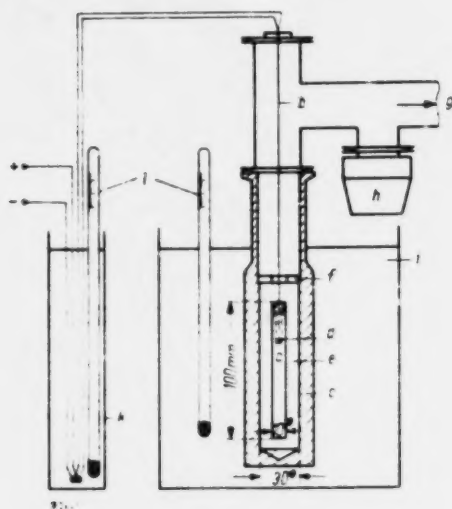


Fig. 1. Diagram of test set-up.

Key: a sample; b thermoelement; c brass tube; d grub screw with soldering point; e borehole; f sealing ring made of brass; g oil diffusion pump; h Penning vacuummeter; i ultra-thermostat; k control measurement point; l mercury thermometer.

Here, ϵ_1 is the emissivity of the sample and ϵ_2 is the emissivity of the tube wall.

Thus, if during the cooling process in the time interval $t_2 - t_1$ the temperature drop in the sample from T_{11} to T_{12} is measured, then, if the values of the emissivity ϵ_2 of the inner wall of the tube, the sample mass M , the specific heat capacity c of the sample material and the sample surface F_1 are known, then the emissivity ϵ_1 of the sample can be determined according to equations (4) and (5). The equations derived also apply for the reverse case of the heating up of the sample.

Figure 1 shows the measurement apparatus. The sample a, a copper rod 100 mm long and with a diameter of 10 mm is suspended centrally on a thermoelement b in the borehole of a brass tube c with an internal diameter of 30 mm. The thermoelement is soldered in the base of a grub screw d 25 mm long that is screwed tightly into the sample with a little grease. The copper rod a can be coated with various

paints, galvanized coating, etc., the emissivity of which has to be determined. Other sample materials can also be used if their specific heat capacity is known and their heat conduction capacity is high enough. For the measurement of the emissivity of glass, for example, the thermoelement was glued in a 0.5 mm borehole in a glass rod with a diameter of 8 mm.

/324

The borehole in which the sample is suspended is coated on the inside with black blackboard lacquer with an emissivity of $\epsilon \approx 0.9$. At the top it is sealed with a brass ring f that has good contact with the wall, so that it takes on the wall temperature. The borehole in the ring is somewhat larger than the diameter of the sample. The hollow space is evacuated using an oil diffusion pump, which is attached at g, to a pressure p of about 10^{-5} Torr. The pressure is measured with a Penning vacuummeter h. The brass tube dips into the bath of an ultrathermostat i by means of which the wall temperature is adjusted and kept constant.

The temperature of the sample is measured by a chromel/alumel miniature thermoelement sheath with an external diameter of 0.34 mm. and compared with a control measurement point k the temperature of which is chosen in such a way that the compensation recorder operates in a favorable measurement range. The temperatures of the control measurement point and the thermostat are measured by a normal thermometer l. The linear recorder serves simultaneously to measure time.

The sample and the bath are brought to different temperatures by rapidly heating or cooling the bath after evacuation of the brass tube. Thus the temperature of the sample slowly approaches that of the bath so that enough time remains for measurement. In order to measure the emissivity of a lacquer for which $\epsilon \approx 0.8$ at the temperature of 30°C , for example, the time is measured in which the sample cools from 31.5°C to 28.5°C . The temperature of the bath is kept at 20°C . As Sparrow [6] has shown, in the case of poor heat conductors the temperature of the wall of the borehole should be used as the reference temperature. Since, however, the change in the emissivity ϵ lies within the measurement accuracy at a temperature change of 10 degrees, the reference temperature is unimportant here.

When the sample cools there is a difference between the sample axis and the surface, especially when the substance samples tested have poor heat conductivity. This temperature difference, based on the temperature in the sample axis, is less than 0.01 degrees if the Biotsch index is $Bi = \alpha_s r / \lambda \leq 0.02$, as can be shown using exact solutions for the heat transport in the temperature field [9] (r = sample radius; λ = heat conductivity). The heat transfer index for the radiation α_2 should be inserted in Bi :

$$\alpha_s = \epsilon_2 \sigma \frac{(T_1^4 - T_2^4)}{T_1 - T_2} \quad (6)$$

In this estimate it can be taken as constant during the cooling process. The measurement should not be done until some time after the initial state, i.e. the Fourier index should be $Fo = a \cdot t / r^2 \geq 0.1$ (a = temperature conductivity). This condition does not affect either the test procedure or the type of sample. On the other hand, the condition $Bi < 0.02$ limits the choice of sample material and the sample temperature, upon which α_s depends, since the sample radius r cannot be made arbitrarily small.

Heat is also removed from the sample by the thermoelement used here, which can be considered a radiation rib. The error arising from this, however, may be about 1% in the case of a silver-coated sample ($\epsilon = 0.02$) or only 0.1% in the case of a lacquered sample ($\epsilon = 0.8$).

The heat flow $\dot{Q}$ that is carried by the diluted gas from the sample to the wall of the borehole is

$$\dot{Q} = \frac{3}{8} p F_1 \left| \frac{3R}{T} (T_1 - T_2) \right| \quad (7)$$

if the average length of the free path of the gas molecules is large compared with the diameter of the hollow space (p is the pressure, F_1 is the cylindrical surface of the sample, R is the gas constant). In relation to the entire amount of heat released during the test period by the sample, the heat conducted from a silver-coated sample is 0.7% and from a lacquered sample it is 0.02%, at a pressure of $p = 10^{-5}$ Torr.

/325

For the deduction of equation (5) the following conditions apply: infinitely long concentric cylinder and the validity of the Kirchhoff Law. Different exchange conditions can be expected on the front sides of the sample. However, this effect can be disregarded with this test arrangement. The borehole in the brass ring that is located opposite the head of the sample can be considered a black surface of the ambient temperature. In the least favorable case, the radiation exchange of the sample with this surface causes an error of 0.4%. Under less favorable conditions, e.g. high sample temperatures, it may be necessary to attach a radiation shield.

A sample that is not suspended concentrically produces a different radiation exchange relationship relative to concentric suspension; this can be estimated using Jakob [10]. For the excentricities that may be expected, in no case is there a perceptible effect on the measurement of ϵ . Since the temperature difference between the sample and the wall of the hollow space is only about 10 degrees and at such low temperature differences the wavelength relationship of the emitted radiation essentially does not change, the conditions for Kirchhoff's Law are maintained.

An estimate of the errors caused by the test arrangement shows that for a metal sample ($\epsilon = 0.03$) an error of 2% can be expected, while for a lacquered sample ($\epsilon = 0.8$) an error of 1% can be expected.

Other sources of error can be found in the limited measurement accuracy of temperature and time and in the sometimes imprecise knowledge of the specific heat capacity c of the sample material. The temperature and time measurement cause at the most an error of 0.8% under these test conditions.

Measurement results

In order to test the apparatus, the emissivities of silver-coated copper, polished brass and polished copper were measured in the temperature range of 10°C to 80°C. The findings are shown in Fig. 2. A comparison with values from the literature is difficult, since metal surfaces have radiation properties that are difficult to reproduce. For example, for silver values are given for ϵ between 0.013 and 0.026 and for polished copper values between 0.02 and 0.04. The

Table 1:

Measured emissivities

[Key on foll. page]

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Nr.	Probe	δ [mm]	20°C	90°C
1	Kupfer versilbert, poliert		0,022	0,023
2	Messing poliert		0,056	0,058
3	Kupfer poliert, Schmirgelriefen sichtbar		0,035	0,038
4	schwarzer Herbol- Schultafellack, gestrichen		0,895	0,856
5	Herbol-Silberlack, gestrichen		0,436	0,414
6	Herbol-Silberlack, getaucht		0,380	0,350
7	farbloser Alkydharz- Lack F 68 auf Silber		0,706	0,679
8		0,030	0,725	0,694
9		0,075	0,832	0,807
10		0,110	0,850	0,820
11		0,150	0,888	0,869
12	desgl. auf schwarzem Untergrund	0,06	0,906	0,886
13	weißer Alkydharz-Lack F 68 auf Silber	0,025	0,817	0,726
14		0,06	0,848	0,806
15		0,01	0,875	0,854
16	desgl. auf schwarzem Untergrund	0,12	0,889	0,880
17	roter Alkydharz-Lack F 68 auf Silber	0,05	0,796	0,748
18		0,075	0,844	0,807
19		0,09	0,866	0,844
20		0,12	0,883	0,862
21	desgl. auf schwarzem Untergrund	0,11	0,894	0,880
22	klarer Alkydharz-Lack L 52 auf Silber	0,025	0,687	0,656
23		0,045	0,771	0,743
24		0,08	0,836	0,808
25	desgl. auf schwarzem Untergrund	0,10	0,914	0,900
26	Aluminium-Bronze L 52		0,474 (0,475) *	0,464 (0,460) *
27	AR Glas (Glaswerke Ruhr)		0,841 (0,846) *	0,861 (0,852) *
28	Kupfer versilbert, poliert leicht mit Litholen eingefettet		0,230	0,225
			30°C	40°C
29	Polyäthylen (Lapolen R) klar auf schwarzem Unter- grund, gefettet	0,35	0,880	0,874
30	desgl. auf Silber, gefettet		0,777	0,769
31	rot, auf schwarzem Untergrund, gefettet	0,25	0,872	0,867
32	desgl. auf Silber, gefettet		0,685	0,680
33	weiß, auf schwarzem Untergrund, gefettet	0,20	0,865	0,860
34	desgl. auf Silber, gefettet		0,777	0,770

* Measurements taken from
Lohrengel [11].

Key to Tab. 1:

1 copper, silver-coated, polished; 2 brass, polished;
 3 copper, polished, emery grooves visible; 4 black Herbol black-board lacquer, painted; 5 Herbol silver lacquer, painted;
 6 Herbol silver lacquer, dipped; 7 colorless alkyd resin lacquer F 68 on silver; 12 the same, on a black background; 13 white alkyd resin lacquer F 68 on silver; 16 the same, on black background;
 17 red alkyd resin lacquer F 68 on silver; 21 the same, on black background; 22 clear alkyd resin lacquer L 52 on silver;
 25 the same, on black background; 26 bronze-aluminum L 52;
 27 AR glass (Ruhr Glassworks); 28 copper, silver-coated, lightly polished, greased with lithelene; 29 polyethylene (Lupolen R), clear, on black background, greased; 30 the same, on silver, greased; 31 red, on black background, greased; 32 the same, on silver, greased; 33 white, on black background, greased; 34 the same, on silver, greased.

emissivities of the samples tested lie within this range.

Table 1 lists the emissivities measured for a number of samples. All the lacquers were applied with a brush to the sample bodies. With the exception of the Herbol silver lacquer (sample 5), no brush strokes were visible after the lacquer application. Therefore the silver lacquer was also applied to the sample body by dipping. This sample shows a much lower emissivity than the one coated with a brush.

As the measurements show, Fig. 2, the emissivity of all the substances studied in the temperature range of 20°C to 90°C depends linearly on the temperature. Table 1 gives the emissivities measured for two temperatures. The emissivity can be determined for the temperatures in between by means of linear interpolation.

All the lacquers show a slight decrease in emissivity with the temperature. For all the alkyd resin lacquers, including the pigmented ones, the emissivity increases with increasing layer thickness if the background reflects well, as Tab. 1 shows. In the case of a poorly

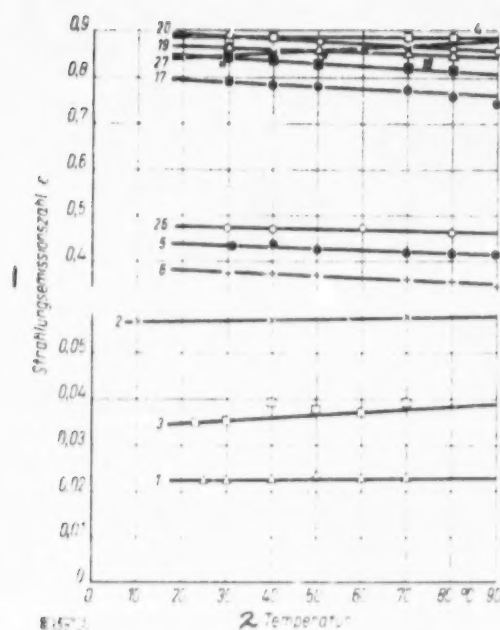


Fig. 2. Radiation emissivity of various substances in relation to temperature. Figures on the curves refer to the samples in Tab. 1.

Key: 1 radiation emissivity ; 2 temperature.

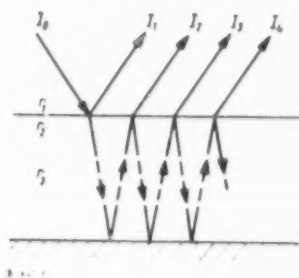


Fig. 3. Multiple reflections on an absorbent layer on a non-permeable background.

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reflecting background, if the sample has previously been coated with black lacquer the emissivity is essentially independent of the layer thickness. /326

In addition, the emissivity of polyethylene was measured. Strips of polyethylene film about 1 cm wide are wrapped around the sample rod. The copper rod first had lithelene vacuum grease ²⁾ rubbed into it, to ensure good contact. The polyethylene film (Iupolen-R) was unpigmented or had white or red pigment. The film samples were each wrapped on a black-coated and a silver-coated sample rod. The emissivity could only be measured within a small temperature range, as at higher temperatures the film peeled off in places, which caused faulty measurements. The white pigment obviously changes the absorption properties greatly, as a comparison of pigmented and clear films shows. Since the lithelene grease used as a contact agent also changes the radiation properties, cf. samples 1 and 28, these measurements are not discussed further in the following section.

Lohrnegel [11] has determined by means of precision measurements of the radiation energy the emissivity of glass and bronze-aluminum L-52, see samples 26 and 27, Tab. 1, in good agreement with our own measurements.

Emissivity of permeable layers on a non-permeable background

The following model, Fig. 3, can be set up for the emissivity of an absorbent layer on a reflective background:

The portion r_1 of the arriving radiation I_0 is reflected on the surface of the layer. The portion $1 - r_1$ penetrates into the layer. The fraction r_3 of this again reaches the underside of the interface, from which the portion r_2 is reflected and the portion $1 - r_2$ passes to the outside through the interface. The portion reflected on the interface into the layer is re-reflected according to the pattern described. The portions $I_2, I_3, I_4 \dots I_n$ that pass to the outside become smaller and smaller.

²⁾ Manufacturer: Leybold-Heraeus GmbH & Co., Cologne-Bayenthal.

$$\rho = \frac{1}{I_0} \cdot \sum_{i=1}^{i=\infty} I_i \quad (8)$$

can be calculated according to Brockes [12] using the defined reflectivities:

$$\rho = r_1 + (1 - r_1)(1 - r_2)r_3 / (1 - r_2r_3). \quad (9)$$

The reflectivities r_1 and r_2 have been calculated by Ryde [13] for a smooth surface. They depend on the refractive index n of the layer material and on the angular distribution of the radiation. In the present case the values should be assumed to be for diffuse radiation.

The reflectivity r_3 is measured according to Kubelka and Munk [14]. The light scattering in the layer can be disregarded here, since the pigment particles are small in relation to the wavelength of the radiation.

If the layer thickness is much smaller than the sample diameter, then there is a plane problem. Kubelka and Munk have looked at a plane-parallel coating with the thickness δ , that is diffusely irradiated. The radiation that penetrates into the coating layer with the intensity i is reduced by absorption into the layer. The radiation coming from below as a result of reflection has the intensity j , which is also reduced by absorption.

In a thin layer dx , see Fig. 4, the intensity is reduced by dj or di :

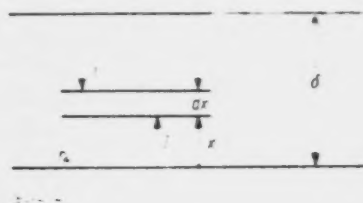


Fig. 4. Model for absorption in the lacquer layer and reflection on the background.

$$E_j = -k j dx; \quad d i = k i dx.$$

/327

(10a)

k is the absorption coefficient. On the background, $x = 0$,

$$(j/i)_{x=0} = r_4. \quad (11)$$

Given this peripheral condition, one obtains the reflectivity r_3 :

$$r_3 = (j/i)_{x=\delta} = r_4 e^{-2k\delta}. \quad (12)$$

This perspective is important for the case in which a coating is applied to a metallic surface. The reflectivity of the metal surface for the radiation from the coating layer is more or less equal to the reflectivity for the radiation from the vacuum. From the equations (9), (12) and the Kirchhoff Law we get, taking into account the relation $\rho + \alpha = 1$:

$$\varepsilon = 1 - \left[r_1 + \frac{(1 - r_1)(1 - r_3)r_4 e^{-2k\delta}}{1 - r_2 r_4 e^{-2k\delta}} \right]. \quad (13)$$

The reflectivities r_1 and r_2 are given by the refraction index n of the layer material. Thus equation (13) gives the connection between the emissivity ε of the coated surface, the refractive index n of the layer, the emissivity of the background and the layer thickness δ . The absorption coefficient k can be determined from a measurement of the emissivity if the background is highly reflective.

In the case of large layer thicknesses or backgrounds with low reflectivities (black background) the second expression in equation (13) disappears. The radiation that has penetrated into the layer is absorbed. Therefore, the reflectivity r_1 can be determined from the measurement of the emissivity if the background is black, $r_1 = 1 - \varepsilon$. In this way, according to Ryde [13] the refractive index can be estimated and the reflectivity r_2 can be determined.

Figure 5 shows the emissivity of red alkyd resin lacquer for a silver-coated and a black background, samples 17 to 21, Tab. 1, regardless of the layer thickness.

While, in the case of the black background the emissivity is essen-

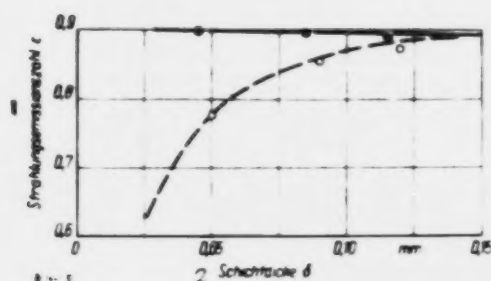


Fig. 5. Emissivity of red alkyd resin lacquer F 68 in relation to the layer thickness.

• black background; ○ silver-coated background; ---- calculated acc. to equation (13) with $k = 12 \text{ mm}^{-1}$; — equalization curve for measurements with black background.

Key: 1 radiation emissivity ϵ ; 2 layer thickness δ .

Table 2. Optical constants for calculating the emissivity of alkyd resin lacquers.

1 Probe	r_1	n	r_2	k (mm^{-1})
klarer Alkydharz: Lack F 68 2	0,103	1,57	0,637	13
weißer Alkydharz: Lack F 68 3	0,116	1,66	0,678	15
roter Alkydharz: Lack F 68 4	0,114	1,65	0,674	12
klarer Alkydharz: Lack L 52 5	0,093	1,51	0,602	16

Key: 1 sample; 2 clear alkyd resin lacquer F 68; 3 white alkyd resin lacquer F 68; 4 red alkyd resin lacquer F 68; 5 clear alkyd resin lacquer L 52.

tially independent of the layer thickness, it increases in the case of the silver-coated background, $r_4 = 0.978$, with increasing layer thickness. From the measurement of the emissivity ϵ with a black background it is possible, as shown above, to determine the reflectivity r_1 , the refractive index n , and the reflectivity r_2 , and in

the case of a silver-coated background and a layer thickness $\delta = 0.05$ mm, using equation (13), the absorption coefficient can be calculated as $k = 12 \text{ mm}^{-1}$. Using these absorption coefficients it is also possible to describe well the measurements for other layer thicknesses. This behavior is also demonstrated by the other alkyd resin lacquers. The optical constants measured are listed in Tab. 2: the absorption coefficients for the lacquers studied have about the same value.

Conclusions

The measurement procedure described is especially suitable for determining the hemispherical emissivity ϵ of paints, metals and metallic coatings. The temperature range of the measurements can be extended even further in both directions.

The measurements of the emissivities of alkyd resin lacquers on highly reflective backgrounds showed that the theories that have been developed for the reflective properties or the covering power of lacquers relative to visible light can also be used to describe the emissivity for ultrared radiation.

Using the same method and the same apparatus, two other substance values can be determined: the specific heat capacity, if the emissivity is known, and the heat conductivity of gases and gas mixtures when convection is excluded, which can be achieved by means of sufficiently low gas pressure or by appropriate dimensioning of the sample and the hollow space. For this measurement the heat is passed through the ring gap between the rod and the tube wall, which is filled with gas.

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/327

/328

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